UK Energy Research Centre

UK Energy Strategies Under Uncertainty

Synthesis Report

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Executive Summary

This report examines the key uncertainties facing the UK's planned low carbon transition, and identifies policies and strategies to mitigate or better understand them. It focuses on technical, economic, political and social uncertainties that could affect the achievement of agreed climate change targets between now and 2030.

The report shows that action can be taken to mitigate many of these uncertainties. In cases where it is not possible to significantly reduce them – at least in the short term – complementary strategies can be pursued. These include providing support for a diverse range of potential technologies and measures, and using trials and evaluations to identify those that are most effective. They also include making greater use of analytical tools that improve understanding of uncertainties and their potential impacts.

The report reaches the following main conclusions:

1. Power sector decarbonisation by 2030 is essential if the UK's emissions targets are to be met whilst minimising the costs of doing so. Whilst this will require large amounts of capital investment, there is no shortage of capital per se. However, further changes to policy frameworks, market structures and business models may be needed to attract that capital to the UK power sector.
2. A limited range of large-scale low carbon electricity generation technologies can have an impact before 2030. All of them face economic, technical and political challenges. Given the financial resources required and the political tensions with some of these technologies, it will be tough for the government and industry to maintain momentum on all of them. It is therefore essential that any decisions to prioritise particular technologies are evidence-based.
3. In contrast to the power sector, there is more flexibility with respect to heat and transport decarbonisation. Whilst there has been a focus on electrification of these sectors, other routes to decarbonisation (e.g. district heating or hydrogen vehicles) may also be significant. Since it is not yet clear what will be the best routes for reducing emissions in these sectors, a continuing emphasis on experimentation, demonstration and learning is needed. In many cases, these demonstrations should focus on non-technical factors such as consumer attitudes, business models and the extent to which regulatory frameworks need to change.
4. One corollary of this greater flexibility is the need for more action in the short-term on energy efficiency, particularly in buildings. Further progress with energy efficiency can help to buy time if the deployment of low carbon technologies is not as successful as planned. Energy efficiency is also an effective way to help to reduce consumers' bills, especially if fossil fuel prices remain high
5. Engagement with people and communities is an essential component of the UK's low carbon transition. Genuine engagement is needed so that public attitudes to energy system change – and not just to individual technologies - are taken into account. This engagement should also focus on how the shift to more sustainable energy systems should be organized and paid for. This approach could not only increase the chances of public support for change, it could also open up possibilities for compromise
6. There are significant risks to scaling back the UK's low carbon ambitions, as some have advocated. It would prolong the UK's reliance on a fossil fuel based energy system, and the exposure of consumers and the UK economy to the potential impacts of high fossil fuel prices. However, natural resource issues will also be important if the low carbon transition continues as planned, albeit to a lesser degree. Controversies and concerns about some of these resources – particularly shale gas and biomass – may limit the extent to which they can be developed and used.
7. The transition to a low carbon energy system will have uncertain implications for ecosystems, both in the UK and globally. Our review of the evidence on ecosystem impacts of major power generation technologies suggests that low carbon technologies will have fewer and/or less serious impacts than fossil fuels. However, it also shows that the evidence base is weak and that significant further research is needed to strengthen this evidence base.

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1

Introduction

The UK faces multiple uncertainties in pursuing its energy and climate change goals. In a challenging economic climate, UK energy futures have become more uncertain and contested. Contrasting energy priorities are being articulated in public policy and in the private sector, exacerbated by controversies over energy prices and bills, shale gas development, onshore wind power and new nuclear power stations.

Despite this contestation, the UK remains committed to ambitious climate change targets, underpinned by the Climate Change Act 2008. The Climate Change Act established a target for the UK to reduce its greenhouse gas emissions by at least 80 per cent compared to 1990 levels by 2050. Under the terms of the Act, four carbon 'budgets' have been agreed and legislated which provide a pathway for emissions reduction from 2008 to 2027. The fourth carbon budget, covering the period 2023-2027, was agreed by the government in 2011 on the condition that it could be reviewed (CCC, 2013a; CCC, 2013b).

When it was passed, the Climate Change Act received strong cross-party support. However, more recent rises in energy prices, the impact of the 2008 financial crisis and heightened concerns about energy security have challenged this consensus.

For decades, successive UK governments have emphasised three energy policy objectives (Pearson & Watson, 2011): security, sustainability and affordability. The relative importance and nature of these goals has changed over time, and they have sometimes been joined by other objectives such as industrial development.

While climate change has been high on the UK energy policy agenda for over a decade, and it remains centrally important, recent statements from government Ministers show that energy policy is once again in a state of flux. Energy Minister Michael Fallon MP provided his own view on the order of policy priorities in a speech in late 2013, which confirmed that climate change mitigation is subject to increasing trade-offs with other objectives within government.

> "Security of supply, affordability, and playing our part in combating climate change. And that for me is the order [of priorities]"
>
> *Rt Hon Michael Fallon MP, December 2013*

The focus on affordability has been particularly prominent in policy and political debates due to steep rises in energy bills since the mid 2000s, and heightened by the Labour leader Ed Miliband's pledge that a future Labour administration would implement a price freeze.

The Chancellor of the Exchequer, George Osborne MP, also concentrated on energy costs in his 2014 budget speech, and on the technologies and policies that, in his view, would bring costs down:

> "We need to cut our energy costs. We're going to do this by investing in new sources of energy: new nuclear power, renewables, and a shale gas revolution. We're going to do this by promoting energy efficiency"
>
> *Rt Hon George Osborne MP, March 2014*

The Secretary of State for Energy and Climate Change, Ed Davey MP, has also placed more emphasis on energy security and affordability recently – and has sought to integrate these objectives with climate change mitigation. In a recent speech, he argued that:

> "Our energy security is best served by minimising our exposure to the volatile global fossil fuel markets, enhancing our energy efficiency and maximising home-grown low carbon energy, as well as cleaner indigenous reserves, such as natural gas, to help ease the low carbon transition"
>
> *Rt Hon Ed Davey MP, March 2014*

These tensions over the goals of energy policy have added to a range of other uncertainties about whether and how the UK's climate change targets can be met. Since the scientific case for a continuing commitment to these targets is very strong (CCC, 2013a; IPCC, 2014), these uncertainties should be analysed in detail so that policies and strategies can be implemented to manage or mitigate them.

Against this background, this report presents the results of an in-depth critical appraisal of uncertainties facing UK's low carbon transition to 2030. It focuses in particular on uncertainties that could affect the achievability of the fourth carbon budget pathway that was set out by the Committee on Climate Change (CCC) in 2011 (CCC, 2011), and revised in late 2013 (CCC, 2013b). It also pays attention to uncertainties that will be still be important if the UK's carbon emissions do not reduce as planned due to a reduced political commitment to decarbonisation and/or ineffective policies and strategies.

The report draws on detailed research on these uncertainties by a large team from the UK Energy Research Centre (UKERC). It highlights what the key uncertainties are – and what could be done to mitigate them.

The research has two main aims:

- To generate, synthesise and communicate evidence about the range and nature of the risks and uncertainties facing UK energy policy and the achievement of its goals relating to climate change, energy security and affordability.
- To identify strategies for mitigating risks and managing uncertainties for both public policymakers and private sector strategists.

In common with other UKERC research, this report takes a 'whole systems' approach to the analysis of energy uncertainties. It focuses on uncertainties across the entire energy system, including electricity, heat and transport, in an integrated way. It also takes an interdisciplinary perspective that combines insights from engineering, natural science and social science.

The report draws heavily on ten project working papers[1]. Each paper includes a detailed analysis of particular areas of uncertainty. The majority of them discuss the implications of their analysis for the CCC fourth carbon budget pathway.

[1] The 'Energy Strategy Under Uncertainty' project working papers which accompany this report are available online at: www.ukerc.ac.uk/support/Energy+Strategy+Under+Uncertainty+External

The papers focus on:

- Methodologies: conceptual frameworks for analysing uncertainty; the analysis of uncertainty in energy systems models; and natural resource assessment
- Low carbon power generation: investment and finance; and low carbon technology assessment
- Low carbon heat: networks for low carbon heat; and heat demand
- Low carbon transport: the adoption of electric vehicles
- Ecosystem service impacts of low carbon resources and technologies
- Public attitudes and values in relation to energy system futures

The evidence from these working papers has been complemented by research from other UKERC research projects and the wider academic and other literature. The analysis for the project was conducted over the past 18 months through a combination of literature reviews, desk research and new primary data collection.

The remainder of this report comprises four further sections. Section 2 briefly summarises the CCC's advice on the fourth carbon budget, including their recent revisions to that advice. This includes a summary of some of the energy system changes the Committee have argued will be necessary to meet the fourth budget. Section 3 sets out the results of our analysis of the key uncertainties that could affect the UK's progress towards meeting the fourth carbon budget. It includes an analysis of uncertainties for electricity generation, heat and transport (with a particularly focus on electric vehicles). It also includes a discussion of more systemic uncertainties that have the potential to have wider impacts on energy system change, including issues relating to natural resources, ecosystem service impacts and public attitudes. Section 4 brings this detailed analysis together and highlights some of the actions that could be taken to mitigate or manage these uncertainties, and by whom. Finally, section 5 sets out our conclusions.

2

The UK's Medium Term Climate Change Targets

Under the Climate Change Act 2008 the UK is subject to a target of an 80 per cent reduction in carbon emissions by 2050 compared to 1990 levels. To ensure that emissions reduce on a pathway that is compatible with this long-term goal, four statutory carbon budgets have been set for the period from 2008 to 2027, outlining allowable emissions for the traded and non-traded sectors of the economy (see Table 1). The UK comfortably complied with the first budget, and is currently in the second carbon budget period.

2.1 The fourth carbon budget

While the period of the fourth carbon budget (2023-27) falls slightly short of the timeframe for this report (2030), the CCC's analysis of this budget covers the time period to 2030. The CCC's original advice, published in 2011, put forward a 'domestic action' budget of 1950MtCO_2 equivalent. This was accepted by government and legislated for in June 2011 (CCC, 2013b). The overall cost of the budget was estimated at less than 1 per cent of the GDP in 2030. The indicative 2030 target for total GHG emissions is 310MtCO_2e (240MtCO_2, 70Mt non-CO_2), implying a 60 per cent reduction from 1990 levels. The main sectors covered by the budget are the power and industrial sectors, buildings and surface transport, agriculture, land-use change and forestry (see Figure 1).

The period to 2030 is considered particularly important, considering that a yearly 5 per cent reduction will be required from 2030 to 2050 in order for the UK's long term targets to be achieved. The CCC argues that the acceleration of emissions reductions in that period will only be achieved if the right conditions are in place and the appropriate technologies have developed by 2030.

Table 1. UK Carbon Budgets

Time Period	Emissions (MtCO_2e)
2008-2012	3018
2013-2017	2782
2018-2022	2544
2023-2027	1950

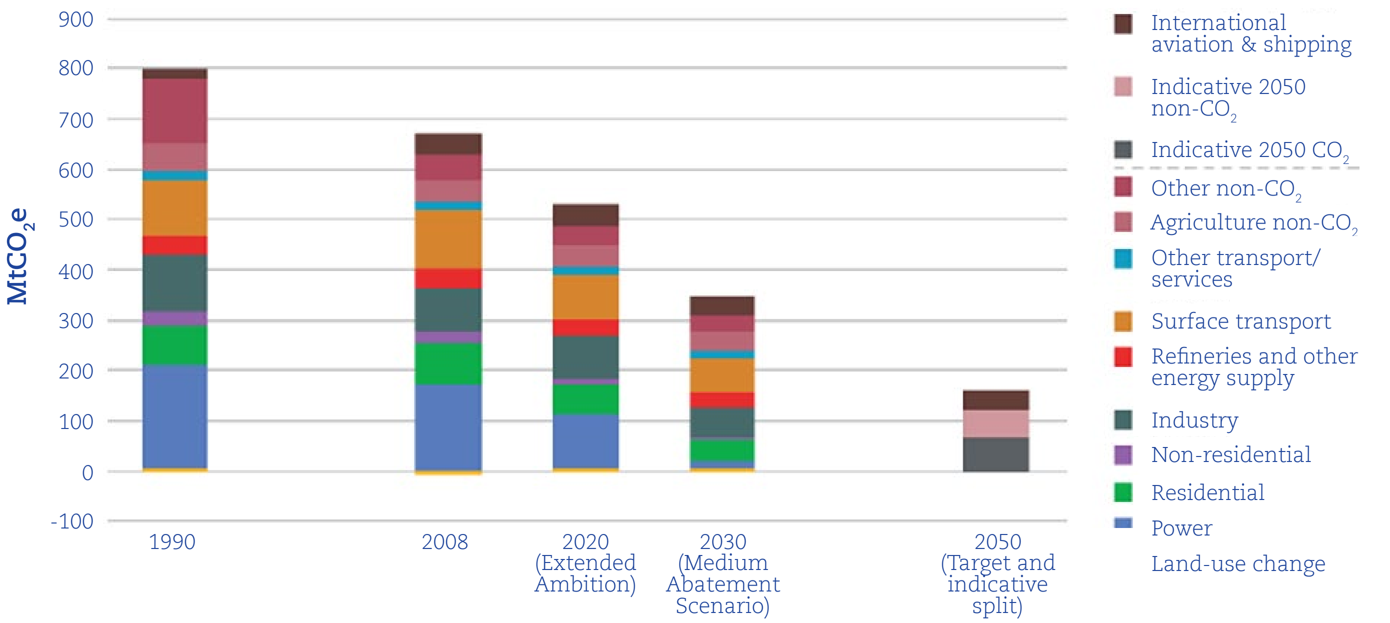
Source: DECC (2009); DECC (2011b)

In common with UKERC analysis (Ekins *et al.*, 2013), the CCC argues that early power sector decarbonisation is crucial under any credible scenario to meet the UK's climate change targets. The carbon intensity of electricity generation should fall significantly, while electricity demand is likely to increase due to the electrification of heat & transport. According to the CCC analysis, the average emission intensity of electricity is required to drop to approximately 50gCO_2/kWh by 2030 through the addition of 30-40GW of low-carbon generating plant during the 2020s. This translates into a minimum build rate of 3GW per year through the 2020s, which should be achieved through a combination of nuclear, fossil fuel plants with CCS and renewables. Due to the emphasis the CCC places on the electrification of the heat and transport sectors by 2050, the power sector may need to approximately double in size by that date, requiring high levels of investment in low-carbon capacity. The CCC notes that annual investment requirements through the 2020s for power generation would reach approximately £10bn.

The electrification of heating for buildings and surface transport are significant aspects of the fourth carbon budget analysis. In terms of building emissions reduction, the CCC's scenarios are largely dominated by electric heat pumps, which are responsible for approximately 70 per cent of emissions reduction potential. By contrast, the development of district heating is limited. Regarding energy efficiency the CCC argues that the focus to 2030 should be on measures where there is limited implementation to 2020, e.g. solid wall insulation. This, in turn, will increase the effectiveness of heat pump deployment.

In terms of surface transport, the CCC analysis expects all new vehicles beyond 2035 to be ultra low-carbon, implying a high rate of adoption by 2030. Battery electric or hybrid electric cars and vans are expected to become cost-effective during 2020s by the CCC, leading to the full phase-out of conventional cars and vans by mid-2030s.

Figure 1. The UK's pathway to a low carbon society. **Source:** Adapted from CCC, 2011.



2.1.1 Revision of the fourth carbon budget

In December 2013 the CCC published a revision of their original fourth carbon budget advice to inform a possible government review of that budget (CCC, 2013b). This included an 'updated abatement' scenario. This most recent analysis uses improved forecasting methods and revised assumptions in many areas covered by the budget. This includes revisions to assumptions about heat pump and electric vehicle uptake, the effectiveness of efficiency measures in buildings and the development of district heating. The updated abatement scenario results in a lower fourth budget of 1690MtCO_2e. This is partly due to decreased baseline emissions projections. It therefore appears that the original budget could be met more easily. Even so, the CCC does not suggest a revision to its original recommended budget. This is based on unresolved uncertainties in the updated abatement scenario and uncertainties relating to EU targets. Moreover, the fourth carbon budget review recommends the same power generation intensity for 2030 (50gCO_2/kWh), even though estimated power sector emissions for 2030 are lower than in the original assessment. Once again, the CCC argues that this would be achieved through the deployment of a portfolio of low-carbon technologies.

The CCC argues that due to reduced abatement potential, solid wall insulation is no longer seen as cost-effective in the revised analysis. However, the importance of solid wall insulation in alleviating fuel poverty is acknowledged. The abatement potential of cavity wall and loft insulation has also been revised downwards, but to a lesser extent. A significant difference is that the updated analysis outlines a lower uptake of heat pumps by 2030. These are projected to be installed in 13 per cent of homes (4 million or 72TWh) by that date instead of 21 per cent (7 million or 143TWh) in the original analysis. This is partly due to updated evidence on capital costs, durability and heat pump performance. Conversely, the expectations for district heating investment have been revised upwards to account for 6 per cent of building heat instead of 2 per cent (30TWh instead of 10TWh).

The expectations for the uptake of EVs have also been revised. The updated analysis for surface transport includes a lower uptake of EVs in 2020. However, the uptake for 2030 remains unchanged at 60 per cent of new cars. While in the original CCC assessment it was expected that EVs would become cost effective during the 2020s, the fourth carbon budget review recognises that high costs are likely to remain as one of the main barriers in EVs uptake for some time to come. The CCC argues that the supply of a variety of EV models options, battery leasing, increased public awareness and improvements in charging infrastructure will help increase the pace and scale of EV adoption. Further 'cost-equivalent' support measures, such as grants, may also be required. The analysis also notes that higher carbon prices would be required to justify increased battery capacities and therefore longer ranges. A slower uptake of EVs in 2030 would delay the point in which low emission vehicles make up 100 per cent of sales to past 2035. The CCC state that this delay would jeopardise the achievement of the 2050 target.

3

Appraisal of the Fourth Carbon Budget Pathway

The decarbonisation of the UK power sector by 2030 has been shown by both CCC and UKERC (Ekins *et al.*, 2013) analysis to be essential to meet our longer-term climate targets while minimising the costs of doing so. This means moving from the current carbon intensity of electricity of 400-500g of CO_2 per kWh to a level closer to 50g/kWh. This section highlights a number of key uncertainties that will affect this aspiration for power sector decarbonisation. This sector faces a level of capital investment in the coming two decades far higher than the previous two decades. It needs to renew its ageing generation fleet, and shift towards capital-intensive low-carbon forms of generation. The decarbonisation of the power sector by 2030 is subject to a range of financial, economic, technological, policy and political uncertainties.

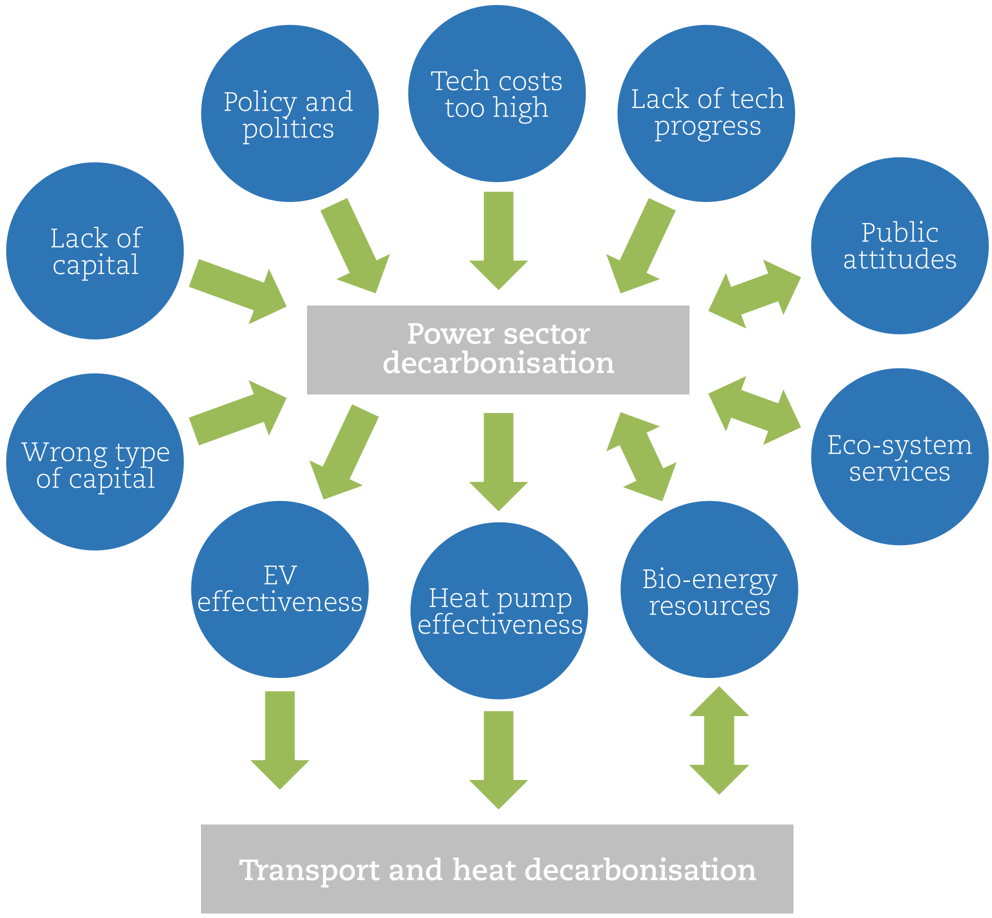
In this section of the report, our analysis focuses on two inter-related areas of uncertainty in particular, and the extent to which these can be mitigated or better understood (see Figure 2). First, the section discusses the availability of financial capital, and the extent to which available capital will be directed into low carbon investments in the UK. Second, it focuses on the extent to which 'technology uncertainties' affect that availability of capital – and whether policy reforms that have been implemented are likely to make such uncertainties manageable for investors. These areas of uncertainty are heavily influenced by other, more systemic uncertainties that are also shown in Figure 2. In particular, uncertainties associated with public attitudes towards energy system change, and the extent to which decarbonisation is aligned with the values associated with these attitudes, are very significant. These uncertainties are discussed alongside other systemic uncertainties (resource availability and ecosystem service impacts) in sections 3.4 and 3.5 of this report.

3.1.1 Will there be enough capital?

Over the past few years, various organisations and commentators have suggested that the UK electricity sector may be unable to deliver sufficient investment in low carbon power generation. Estimates of the size of the investment challenge range from the widely quoted DECC/Ofgem figure of £110bn for electricity generation and transmission by 2020 to much higher figures ranging from £200bn to over £300bn by 2030 (Blyth *et al.*, 2014a). Comparing a range of different published estimates on a like-for-like basis of average annual investment (Figure 3), the average amount of investment required is £6.1bn/year (3.4 GW per year of new capacity) to 2020. This increases to £12.3bn (5.7 GW) to 2030, reflecting the need to expand the construction of capital-intensive low carbon plant, and to account for greater levels of plant retirement, post-2020.

These projected requirements are considerably higher than the average investment rate during the 2000s (£1.1bn/year). This gulf led to concerns about the ability of the sector to deliver the impending investment needs. However, in the investment in power generation was particularly sparse, with only about half the level of investment of the 1990s. More recently since 2009, investment has been scaling up significantly. Over the period 2009-2012, average capacity additions were 4 GW per year, with average annual capital investment of £4.6bn. These are much closer to the estimates of investment needs to 2020 and 2030. In 2012 in particular, wind investment reached 1.9 GW, which compares favourably with an average requirement of 2GW per annum across all future scenarios for the studies reviewed in this report. However, to reach the most environmentally ambitious scenarios, wind investment would need to scale up to around 3GW per year, requiring an extra £2bn annually.

Figure 2. Key uncertainties for decarbonising the power sector to 2030



Recent investment rates therefore suggest that immediate concerns about a large 'gap' in investment may be overstated. However, major questions remain about whether recent rates of investment can be sustained through the period to 2020. There are signs that the reduced demand and other market conditions are causing the major utilities to scale back planned capital expenditure by as much as 30 per cent by 2015 relative to 2012 levels. In the 2000s, utilities took on higher debt levels to fund mergers and acquisitions across Europe. These companies are now attempting to de-leverage their balance sheets in order to maintain reasonable credit ratings and access to the low-cost bonds and shares on which their business model depends. This constrains their ability to raise debt to cover increased investment.

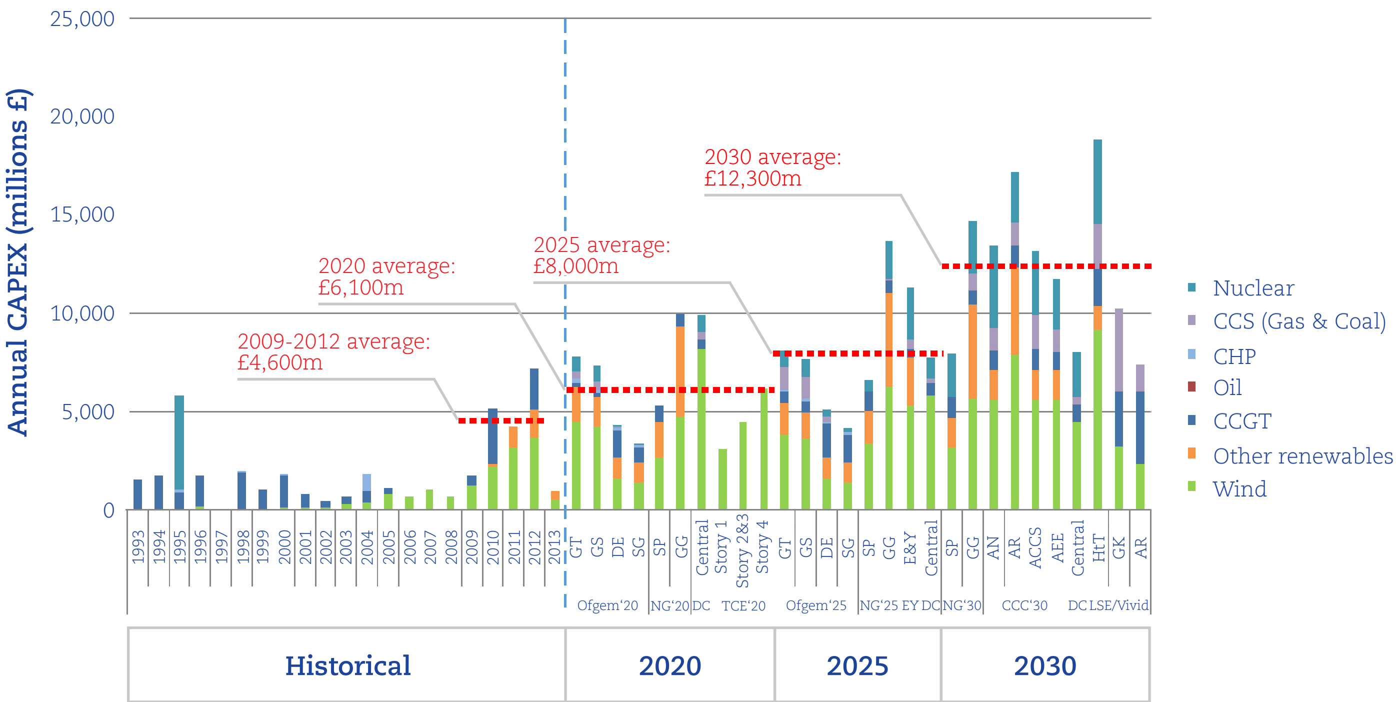
The role of these utilities has varied with respect to the main large-scale low carbon generation technologies. In offshore wind, consortia with multiple investors are usually put together to finance the large scale of investment required. Utilities usually own the majority of the equity, with consortia of banks holding the debt.

The involvement of established utilities provides an important anchor that gives other investors some reassurance that projects will not be abandoned should they run into difficulties. However, current constraints on utilities mean that scaling up offshore wind will probably need to involve a greater diversity of players, with utilities taking a smaller share.

By contrast, individual nuclear power investments are very large, with unique risk profiles. While agreement has only been reached on one nuclear station so far (at Hinkley C), equity investors seem most likely to be utilities or equipment manufacturers, or a combination of both.

Significant guarantees (implicit or explicit) are also very likely to be needed from national governments. The fossil fuel segment of the market could become more diversified depending on the degree to which capacity markets look attractive to independent power producers. Utilities seem likely to play a continued role here too, especially for the large investments required for carbon capture and storage if that technology takes off post-2020.

Figure 3. Financial resources required to decarbonise the power sector



In general, the future role of the big pan-European utilities in the UK depends largely on market conditions, including the extent to which Electricity Market Reform (EMR) is successful. If these companies do not find it attractive to invest in the UK due to the real or perceived risks being too high, it is unlikely that other companies will find it attractive to invest either.

3.1.2 Is investment in the UK power sector too risky?

Finance sector organisations interviewed for UKERC research tended to say there is not a lack of money, just a lack of good projects (Blyth *et al.*, 2014a). While finance is available in principle, the vast majority of money in financial markets is structurally required to be in low risk investments. 90 per cent of funds held by the largest institutional investors are in bonds and shares of investment-grade companies.

While higher risk capital is available, volumes are probably too small to address the scale of infrastructure investment required. Some commentators have suggested that institutional investors could play an increasing role by taking a direct stake in investments rather than investing in utilities (PWC, 2010). Some involvement from such investors has been seen in offshore wind projects, but this is currently at a low level. While the total assets managed by these investors is vast (approximately $70 trillion or £40 trillion), it is highly segmented by region and sector, and the great majority of the money (90 per cent) is dedicated to liquid low-risk assets, such as bonds and shares.

Institutional investment in renewables across Europe was €2-€4bn (£1.7-£3.3bn) per year in 2011 and 2012, with perhaps 10 per cent of this going to the UK. Our analysis suggests that the UK energy sector could see an increase from this source up to perhaps £800m per year (Blyth *et al.*, 2014a). However, this depends on achieving a suitable risk profile for the investments. Institutional investors have tended to prefer assets with guaranteed returns. In the energy sector, these have mostly been in regulated assets such as energy distribution networks.

Another factor which may limit the role of institutional investors is their tendency to prefer low-profile investments with a low degree of public exposure. They may prefer to remain junior partners in energy projects in order to avoid the risk that the current political and public focus on the high costs of new energy sources could turn into increased scrutiny of them (see section 3.5 of this report). This scrutiny has focused on the 'big six' utilities so far, but they also need to make a reasonable return to justify investments in new plants. The problem is that there is no consensus about what such a 'reasonable' rate should be.

At present, the primary focus of government policies such is to get the investment conditions right in the electricity sector, and to try to mitigate investor risks. In the short-term, these policies could be strengthened with a greater role for public financial institutions such as the Green Investment Bank and the European Investment Bank to take direct stakes in projects to leverage other investors in and to accelerate the recycling of pre-construction capital into new projects. Project bonds may start to play a more significant role, but evidence is mixed regarding realistic potential.

An alternative approach would be to completely re-regulate electricity generation using a fixed rate of return model that removes most of the risk for the investor. The downside of this approach in terms of reducing competitive pressures, decreased incentives for innovation and the potential for the pass through of cost over-runs to consumers should not be underestimated. The new contracts for low carbon generation that are being introduced as part of EMR are a half-way house, providing fixed income, though not fixed returns because of uncertainty over construction and operating costs.

In the longer term, ownership structures and the electricity market are set to evolve. Direct stakes in energy projects by institutional investors are currently low, but could grow to a more significant level. Equipment manufacturers often take a stake in offshore wind, and could do so also for nuclear. The capacity mechanism being introduced under EMR could also attract more diverse ownership, and could start to engage the demand side more actively. Combined with the growth of embedded generation, this may alter the characteristics of the market substantially over the next two decades, bringing with it a diversification of financing models for the sector. The impending review by the Competition and Markets Authority could provide an opportunity to revisit the fundamentals of utility business models in the UK, and to open up the energy market to this wider range of investor possibilities.

3.1.3 Technology uncertainties: can they be managed?

The analysis for this report has analysed three categories of uncertainty relating to low carbon power generation technologies (Blyth *et al.*, 2014b):

- Techno-economic uncertainties associated with the economic, environmental and technical performance of individual low carbon technologies;
- Programmatic uncertainties associated with the wider policy, regulatory and institutional arrangements that could affect the development pathways for these technologies; and
- System integration uncertainties arising from the integration of multiple power generation technologies within a low carbon electricity system.

Therefore, some of these uncertainties are specific to the technologies concerned, while others are sufficiently substantial to alter the development pathway of the overall electricity system. The analysis focuses on four specific energy supply technologies: solar PV, offshore wind, carbon capture and storage (CCS) and nuclear power. Table 2 summarises the different types of uncertainty that are associated with each of these options, and with electricity decarbonisation as a whole.

The impact of failure of any individual technology to reach maturity is heightened by the fact that there are relatively few technologies involved in the electricity sector transition envisaged to 2030 under the fourth carbon budget. Many of the most immediate uncertainties relate directly to capital or operating costs, but other factors such as availability and reliability can also have important cost, environmental or security impacts. Potential environmental impacts include the failure of a low carbon technology to fulfil its expected role in reducing emissions. Of course, even if low carbon technologies are reliable, some of them will have impacts on the climate or other ecosystem services (see section 3.4 of this report). Security impacts could play out over a shorter timescale: e.g. a shortfall in generation capacity could occur if plant availability is lower than expected, or if construction takes longer than expected.

Policy assessments of technological uncertainties incorporate financial appraisal and energy system modelling, with an emphasis on costs of generation while investors would also be concerned with revenue risk. Policy-makers are often required to make judgements about the long-term economics of low carbon generation technologies in order to decide what level and type of public policy support to provide (if any). Methods used to inform these judgements include learning curves, and separate assessments for the R&D, demonstration and pre-commercialisation stages of technology development. Technology readiness assessments are used to judge the type of policy support they are likely to need. However, as a recent UKERC evidence review has shown (Gross *et al.*, 2013), forecasting future costs is complicated.

Costs for several power generation technologies increased in the mid-2000s, a development that ran counter to many projections. It partially reversed cost reductions seen in the 1990s. This gives rise to a concern about whether projections of future cost reduction (see Figure 4) are the product of 'optimism bias'. UKERC's analysis found that there are many reasons why costs did not evolve as expected. Some technologies appear more likely than others to benefit from ongoing 'learning effects', which drive down costs as deployment increases.

The report also cautions that historically some analyses failed to anticipate events (e.g. commodity price movements or macro-economic trends) that can undermine or overwhelm learning and innovation. However, the review also identified more rigorous 'appraisal realism' in several recent reports for the UK government, and that awareness of uncertainty about cost trends is improving. It concluded that there is substantial evidence that the costs of new technologies can be brought down through innovation and economies of scale, though this may take some time to occur. Costs can increase in the early stages of deployment due to 'teething troubles'.

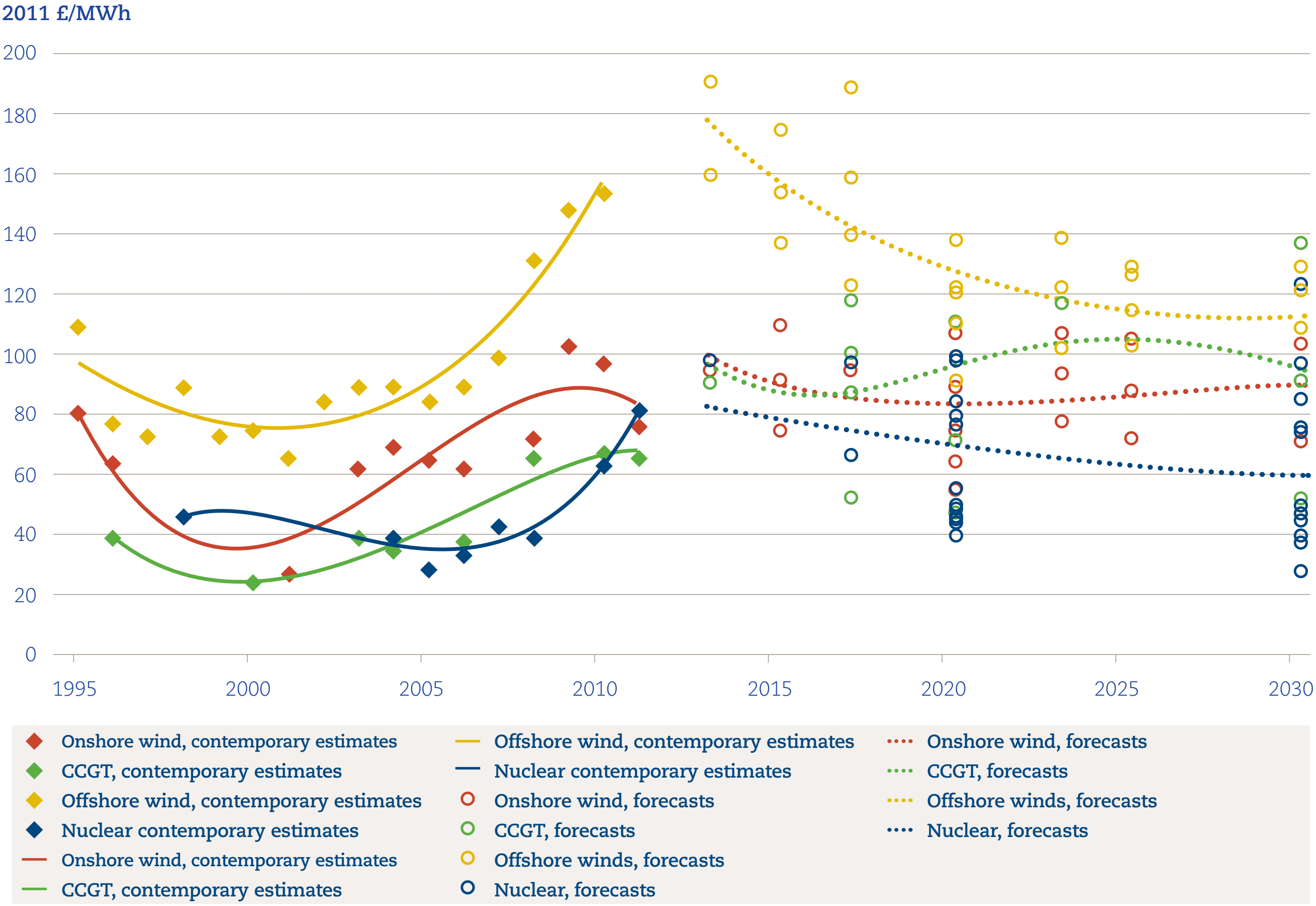
UK funding for technology development and deployment is fragmented, with funding powers distributed across many different public and private bodies. This presents strengths and weaknesses for tackling technical uncertainties. On the positive side, fragmented funding provides a variety of institutional approaches that can be tailored to the specific needs of each 'family' of low carbon technologies. On the negative side, it makes oversight of the innovation process more complex.

Despite efforts at coordination between the various innovation support bodies (e.g. through the Low Carbon Innovation Co-ordinating Group), fragmentation makes it harder to share learning and to identify key areas of programmatic uncertainty. This is exacerbated by the difficulties that all public sector institutions face of dealing with, and learning from, technology 'failures'. Competition between institutions could mean a tendency to focus on opportunities and success, and a lack of attention to innovation issues that affect the whole electricity or energy system. The difficulty of openly identifying and discussing failure is compounded by the political need to show that all low carbon options are kept open.

Table 2. Electricity generation technology uncertainties

	Techno-Economic	Programme	System Integration
Generic	• Economic & financial viability • Uncertainty over future costs • Market conditions (e.g. future demand and fuel prices)	• Policy commitment and support • Public acceptance • Supply-chains for scaling-up • Skills & knowledge • Innovation co-ordination	• Achieving high levels of electricity system diversity • Adapting supply-side options to demand-side flexibility and innovation
Nuclear	• High capital costs & realising reductions • Long-term waste management • Long build times	• Long-term waste management • Regulatory risks associated with safety requirements	• Adapting to changing base-load profile of supply
CCS	• Realising cost reductions • Regulation of CO2 storage • Integration of CCS component systems and skills	• Variety of technologies could fragment development efforts • Scaling-up technology • Realising cost reductions	• Operating CO_2 transport & storage under variable generation profile
Offshore Wind	• Realising cost reductions (capital & operating costs)	• Uncertainty over domestic supply chain	• Integration of intermittent generation: need for storage, demand-side response, interconnection etc.
Solar PV	• Potential volatility of international supply chain costs	• Creating stable price support expectations	

Figure 4. Range of Levelised Cost of Energy (LCOE) estimates, in-year mean and UK-specific forecasts



Source: UKERC analysis

DECC stated in the original Carbon Plan that it will run a 'low carbon technology race' in the 2020s between the main generation technologies to see which of them will deliver emissions reductions at lowest cost (DECC, 2011b). But building up the necessary supply-chains and attracting investment to each of these technologies requires everyone involved to believe that the technology development pathways are possible and credible, and that real and substantial project pipelines will be developed in order to keep firms and investors engaged. In practice, this will continue to require significant political capital as well as financial capital. Contemporary controversies about technologies such as onshore wind and nuclear power suggest that the availability of both political and financial capital will have limits.

Technology uncertainty and failure may also be under-represented in energy system models. Many models use variations of optimisation routines which are built on an assumption of perfect foresight (i.e. they know what future costs and performance will be).

While the perfect foresight assumption is altered or diluted in some models, such methods lack the ability to explore adequately deeper uncertainties such as the potential for sudden disruptive events or technology paradigm shifts. Models can be developed to deal with more uncertainty. For example, the working paper by Pye *et al.* (2014) for this project has included probability distributions within the Energy Technologies Institute energy systems model to explore trade-offs in low carbon energy scenarios. This goes beyond the more usual approach of applying sensitivity analysis to a model: an approach that still tends to assume that everyone involved in a particular pathway or realisation of the world knows where they are going, and no major mistakes or disruptions occur.

The level of contingency planning is probably therefore currently underestimated, and it may be necessary to build more slack into the system. To allow for failure or underperformance in any one or more of the currently planned technology pathways, it would be necessary for the others to expand to compensate.

3.2 Heat decarbonisation

Heat constitutes the single biggest use of energy in the UK (Chaudry *et al.*, 2014). Almost half (46 per cent) of UK final energy consumption is used to provide heat. Of this heat, around 75 per cent is used by households and in commercial and public buildings. The rest is used in industrial processes. Household heating demand is primarily met using gas-fired boilers connected to the natural gas network (81 per cent). The remainder is provided from electricity (7 per cent), heating oil (9 per cent) and from solid fuels such as wood and coal (3 per cent). Use of these other fuels is particularly significant in rural areas where there is no mains gas network (DECC, 2013). Meeting the 80 per cent emissions reduction target for 2050 is likely to require that heat related emissions of CO_2 from buildings are near to zero by 2050, and that there is a 70 per cent reduction in emissions from industry from 1990 levels (Chaudry *et al.*, 2014).

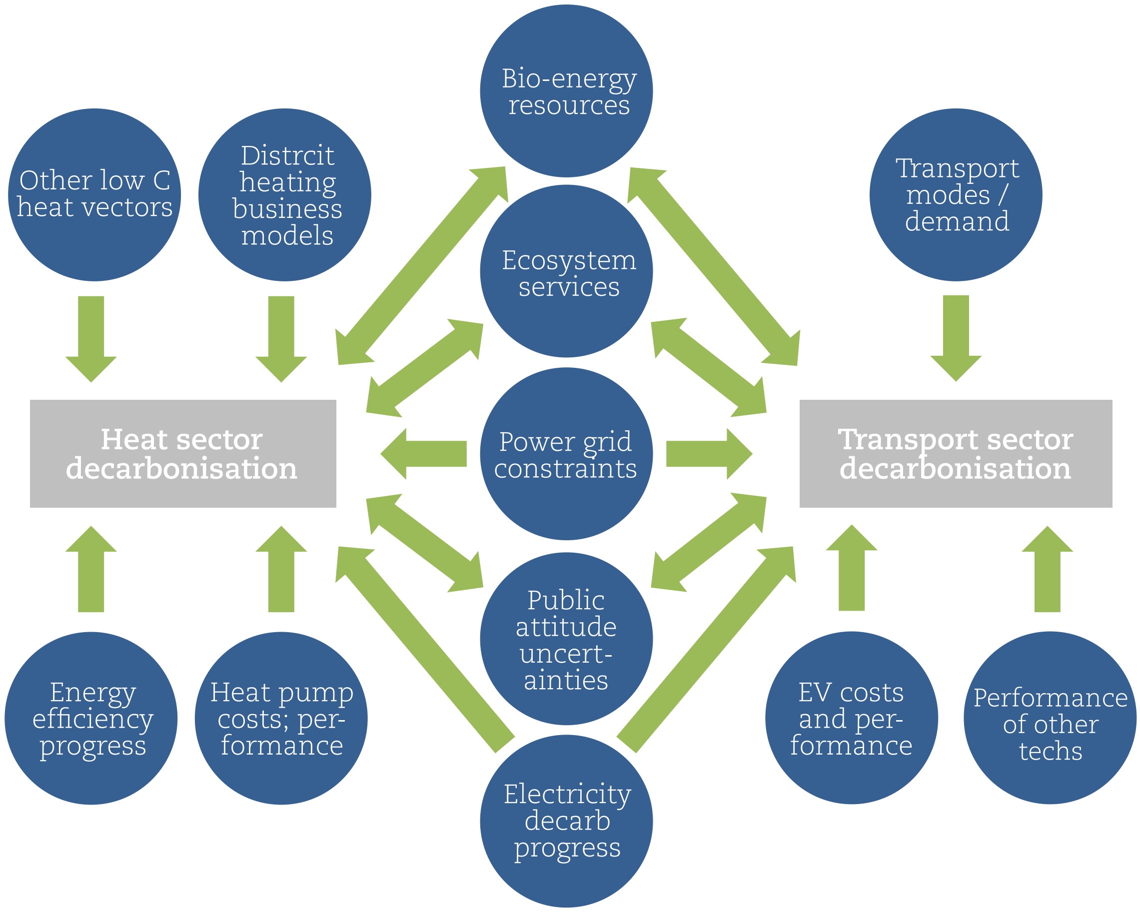
This section draws on two related pieces of research that focuses on uncertainties relating to low carbon heat. First, an investigation of the implications of heat decarbonisation for energy network infrastructures was carried out (Chaudry *et al.*, 2014). This focused on gas, electricity and heat networks. Second, more detailed research was conducted on options for reducing carbon emissions from household heating – and the extent to which different pathways for low carbon heat could be compatible with the CCC's fourth carbon budget pathway (Eyre & Baruah, 2014).

The main uncertainties that were identified for low carbon heat are summarised in figure 5 together with uncertainties for low carbon transport.

As noted earlier in this report, the CCC's revised fourth carbon budget pathway includes a range of actions to reduce emissions from heat – with a particular emphasis on energy efficiency improvements and the deployment of heat pumps. When compared to the CCC's original fourth carbon budget analysis, the level of ambition for heat pumps has been scaled back and the delivery of low carbon heat via district heating networks has been expanded. These adjustments partly reflect uncertainties about the current and future performance of heat pumps, and how quickly households and businesses will adopt them. They also reflect deeper uncertainties about the combinations of network infrastructures, low carbon technologies and energy efficiency measures that will be required to meet statutory targets.

Until recently, many analyses undertaken by the CCC and the UK government tended to emphasise that the primary route to reducing emissions from domestic and commercial space and water heating would be to use low carbon electricity, with a large role for electric heat pumps. However in more recent assessments, this view has increasingly been questioned. The more diverse approach in the CCC's revised fourth carbon budget analysis is also reflected in the government's heat strategy (DECC, 2013). These uncertainties for low carbon heat can be illustrated for the household sector.

Figure 5. Electricity generation technology uncertainties



Figures 6-8 shows a set of four scenarios for domestic heating in the UK between now and 2050. The 'minimum policy intervention' scenario is not compatible with the UK's climate targets. The other three scenarios include significant emissions reductions. A key contrast for this report is between the 'electrification of heat' and 'deep balanced transition' scenarios. The 'electrification of heat' scenario shows how electricity demand could rise significantly if electric heating systems – particularly heat pumps – are installed throughout the UK. By contrast, the 'deep balanced transition' scenario shows a future where the emphasis is on demand reduction and heat networks, with a much smaller role for electricity in the delivery of low carbon heat.

This analysis shows that the main challenge for low carbon heat during the period to 2030 is to start a shift away from the current system of heating which is dominated by natural gas. This is perhaps more important than the electrification of heat per se, given that there are other complementary routes to low carbon heating that would be compatible with the fourth carbon budget pathway. This means that failing to reach the CCC's target for electricity decarbonisation by 2030 (i.e. a carbon intensity around 50g/kWh) would not necessarily have a significant impact on progress with heat decarbonisation by that date.

However, even in scenarios where electrification is less significant, there is still a role for electric heating using low carbon technologies such as heat pumps. This means that the performance of heat pumps, and the rate at which households and businesses adopt them, should continue to receive a significant amount of attention.

The CCC's revised pathway includes heat pump deployment of 72TWh and 10 TWh in the domestic/commercial and industrial sectors respectively. For the domestic and commercial sectors, this represents a 50 per cent reduction on the level included in the original fourth carbon budget analysis. The main reasons for this downward revision are higher investment costs and poorer performance than originally expected (Chaudry *et al.*, 2014).

There are also other significant uncertainties that will affect adoption rates, including the extent to which space is available for installation, consumer attitudes to noise from air source heat pumps, and the relatively high heating requirements of many UK households due to poor levels of insulation. There are also potentially significant implications for the electricity network if adoption is widespread because annual and peak electricity demand would increase significantly. Peaks may be a particular challenge. While short-term storage of heat within buildings can help to mitigate this to some extent, the widespread deployment of heat pumps in the 'electrification of heat' scenario shown in Figure 6 could mean an additional electricity system winter peak load of 40GW.

The amount of heat that will need to be provided by heat pumps and other technologies will be heavily dependent on progress with energy efficiency. The CCC, the government and UKERC's own energy system scenarios (Ekins *et al.*, 2013) have consistently emphasized the importance of energy efficiency and demand reduction measures. In the context of low carbon heat to 2030, our analysis shows that significant energy efficiency progress will also buy time. It will provide space for the diversity of potential technologies and infrastructures that could deliver low carbon heat to consumers to be developed, demonstrated and evaluated. Improved building fabric efficiency also aids the technical performance of heat pumps. However, at very high efficiencies (e.g. Passive House standards), space heating loads are very low and it potentially becomes difficult to justify the cost of more sophisticated heating systems.

From 2004-2012, the long term trend of rising household energy demand in the UK reversed with large, policy driven programmes of loft and cavity wall insulation and condensing boilers outpacing rising service demands. However, this could be seen as an atypical period characterised by the easy availability of energy efficiency improvements and an effective policy framework to deliver them. This trend is now likely to change due to the lower availability of low cost measure and the recent large reductions in UK residential energy efficiency programmes (Rosenow & Eyre, 2013).

An important uncertainty for heat decarbonisation (and indeed for reducing emissions across the energy system) is the extent to which energy efficiency incentives will be strong enough. At some point, however, improvements in the building fabric and/or ventilation will become more expensive than switching to low carbon forms of heat. UKERC's research on household renovations and energy efficiency shows that the marginal cost of high performance refurbishment is surprisingly uncertain, partly because of the issue UKERC research at the University of East Anglia has highlighted (Wilson & Chryssochoidis, 2013) – that the costs are much lower, and projects much more likely to happen, if integrated into broader refurbishment planning.

This analysis also shows that there is a need for further demonstration and early deployment of low carbon heat technologies and associated infrastructures to determine which solutions work best in which contexts. While technologies such as district heating and heat pumps are not particularly novel, their levels of deployment are relatively low in the UK. Demonstration and testing is therefore an opportunity to develop financial models, explore regulatory changes that may be necessary (for example, heat networks are not subject to economic regulation), and to engage householders, businesses and other organisations. Initiatives such as the ETI's smart systems and heat programme are therefore welcome.

Heat networks will only be useful in the long-term if heat is produced from low carbon energy sources. Natural gas fired district heating can only reduce emissions so far – and is unlikely to help reduce emissions once electricity grid carbon intensity falls below 250 g/kWh. As the scenarios in Figures 6-8 show, district heating (or indeed for smaller heat systems) can be flexible, and can use bioenergy or biogas instead of natural gas. However, as discussed in section 3.4 of this report, there are potentially competing demands for bioenergy resources – or the land that would be used to grow them – which could also be potentially used for power generation and transport. There are also significant sustainability concerns about the use of bioenergy (Slade *et al.*, 2010).

The main challenges for district heating implementation in the UK are non-technical. Barriers to implementation include constraints on the availability of finance available to Local Authorities who have a key role to play in developing district heating schemes. The up-front costs of these schemes can be substantial, and there is also a lack of relevant skills and knowledge within many Authorities. Furthermore, there may be issues of public acceptance, especially in cases where a switch from conventional individual heating systems is envisaged.

Overall, low carbon heating technologies and their associated infrastructures can be thought of a complementary rather than competitive. For example, district heating could enable larger and more efficient heat pumps in future.

Figure 6. Electricity demand in UK residential heating scenarios

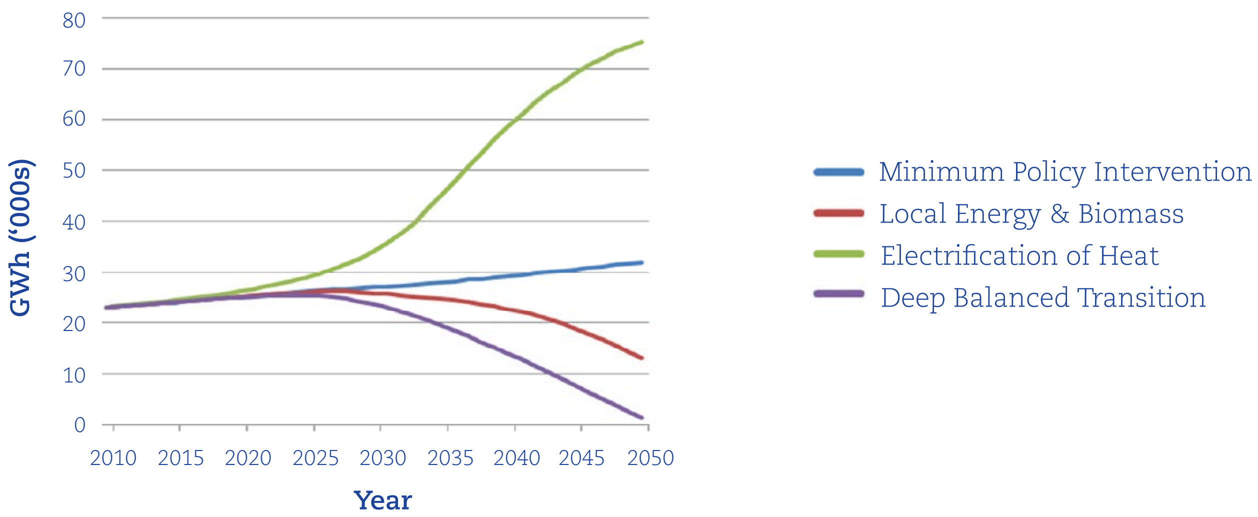


Figure 7. Gas demand in UK residential heating scenarios

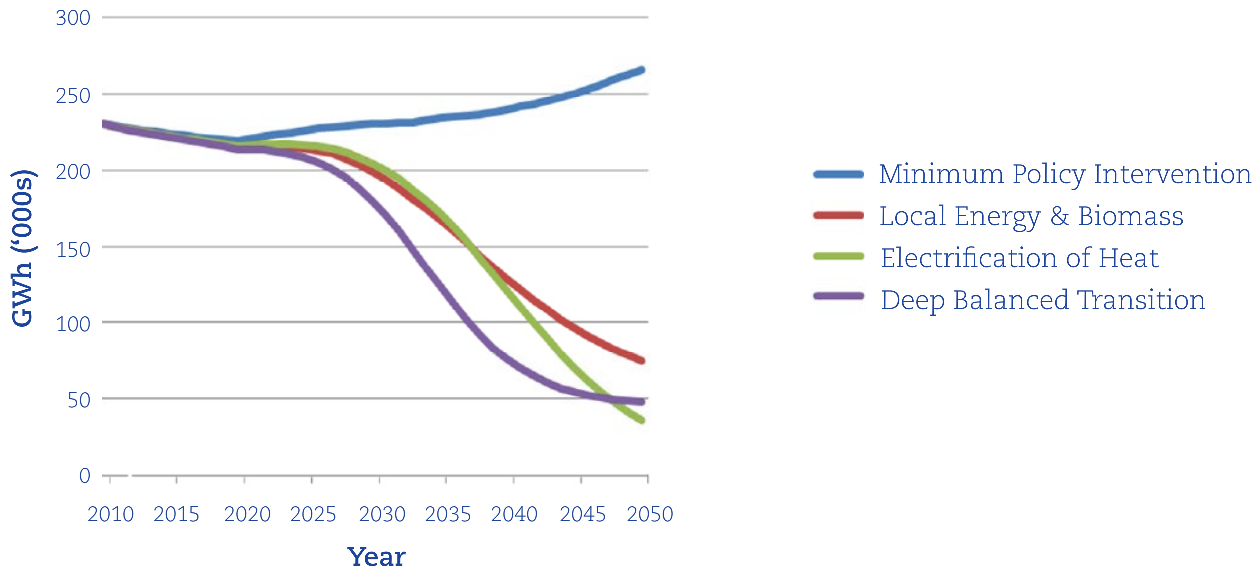
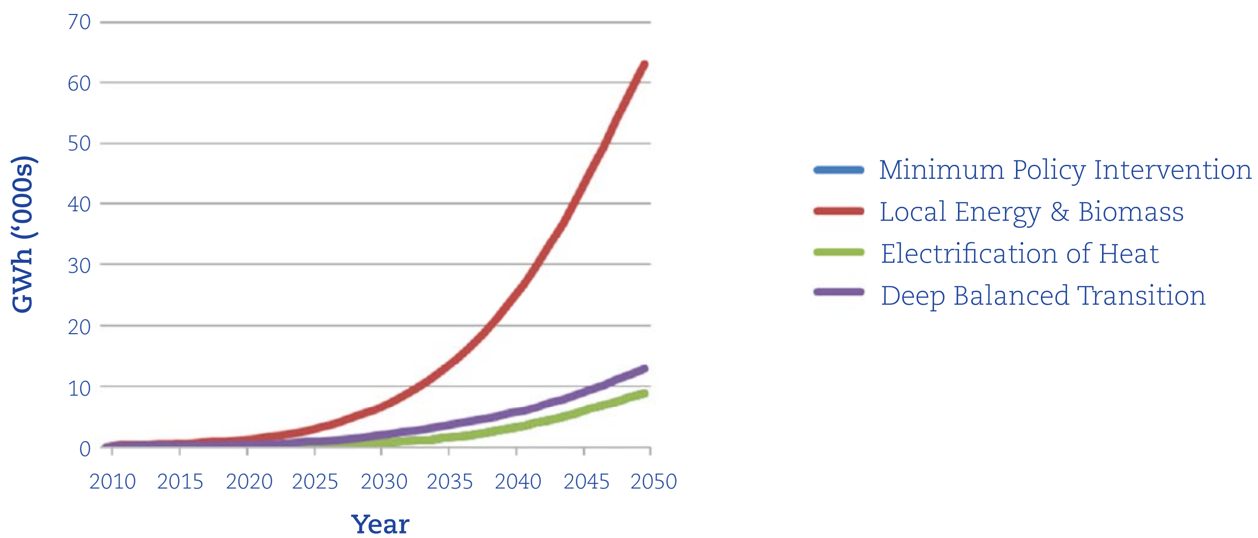


Figure 8. Bio-energy demand in UK residential heating scenarios



A combination of heat pumps and district heating could be beneficial for electricity load profiles and there is also potential for other solutions such as improved electrical storage heaters or hybrid heat pumps. By using gas to meet peak heating loads, these do not require the same amount of power capacity or grid infrastructure expansion. Ground source heat pumps have higher efficiencies, but air source heat pumps are likely to be more suitable in suburban locations that are space constrained. The use of bioenergy for heating might be unsuitable in dense urban environments, whereas bioenergy supplied as biogas or via district heating might be acceptable. A large number of uncertainties clearly remain to be resolved, but it is clear that natural gas dependence will need to be reduced, and that a range options to replace gas need to be demonstrated, evaluated and deployed.

3.3 Transport decarbonisation

As with heating, there are a number of routes for decarbonisation of surface transport. In our analysis, we have focused in particular on private road transport and the potential for Electric Vehicles[2] (EVs). This was partly driven by the importance of EV roll out in the Committee on Climate Change's analysis of required emissions reductions to 2030, and reflects the greater policy and industry emphasis on EVs in comparison to other low carbon options such as biofuels and hydrogen vehicles. However, it is important to recognize that these other options also have significant potential – and are being actively supported to some extent by current UK policies.

Emissions in the transport sector are motivated by a complex array of factors inclusive of, but not limited to, the spatial distribution of the built environment, working practices, population demographics and habits of consumption (Banister & Anable, 2009). With these points in mind, it is important to recognise that technological innovations such as EVs are likely only to offer a partial, though potentially significant, contribution towards the decarbonisation of surface transport. Moreover, enthusiasm towards EVs should perhaps be tempered by the previous occurrence of 'hype cycles' in this sector (Budde *et al.*, 2013), most clearly seen in the expanding and subsequently contracting interest in hydrogen and biofuel vehicles during the past decade or so.

The revised fourth carbon budget analysis has reduced the level of ambition for EV adoption by 2020. It maintains the target for 2030 that 60 per

cent of new car and van sales should be EVs, but reduces the proportion for 2020 from 16 per cent to 9 per cent of new sales (CCC, 2013b). There were only 1742 new registrations of EVs in 2012, which accounted for 0.08 per cent of total new car registrations (DfT, 2013). In order to reach the sales requirements estimated by the Committee of Climate Change, registration rates of EVs will have to double every year to 2020. To provide some context for the scale of this challenge, the average annual growth in registrations of Hybrid Electric Vehicles in the UK between 2005 and 2012 was 17.5 per cent.

Our research on EVs identified a range of factors and uncertainties that influence the rate of EV adoption, and assessed the extent to which current policies and strategies are mitigating these uncertainties effectively. The evidence is based on a series of expert interviews, including with some early adopters of EVs. Figure 9 provides an illustration of the areas of uncertainty that were identified. These areas include uncertainties associated with the drivers of consumer decision-making, including the infrastructure, technological and policy uncertainties that impact directly on this process.

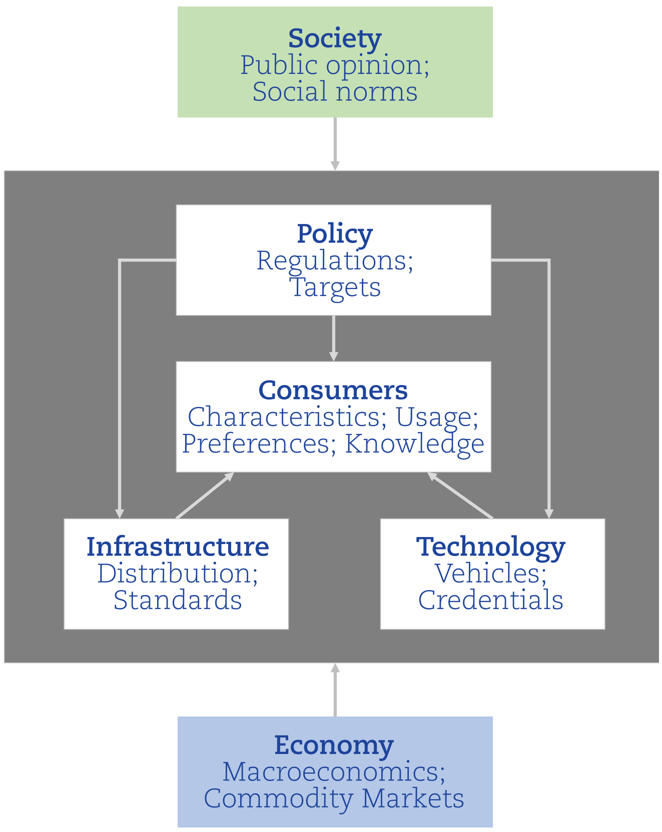
To some extent, policies have already been put in place to mitigate some of these uncertainties, such as the installation of EV charge points under the Plugged-in Places initiative to reduce infrastructure uncertainties. In addition, the significant commitment of government funding to support the development of the EV market has reduced policy uncertainty. In addition to these uncertainties, broader economic and societal uncertainties were identified such as the legitimacy of EVs as a desirable option for consumers, and developments in national and international economic conditions and fossil fuel prices.

[2] Inclusive of plug-in hybrid electric vehicles and pure battery electric vehicles

These are less amenable to mitigation through government policy – and are related to the systemic uncertainties that are discussed in later sections of this report (see sections 3.4 and 3.5).

This analysis identified three areas of uncertainty that are particularly significant, and that can be reduced to some extent by additional policies and strategies (Morton *et al.*, 2014). First, while there is generous financial support for the adoption of EVs (in the form of upfront grants), there is significant uncertainty about other forms of support such as the length of the moratorium on fuel duty for EVs and the lower rates of registration and road tax that are currently applied. Longer term certainty over these taxes would make it more likely that some consumers would adopt EVs – and would improve their overall life cycle economics. Related to this, our research revealed concern about the durability of policy commitments to EVs. Second, the lack of an integrated payment mechanism for EV charging is creating significant inconvenience and confusion for EV users – a situation that could be alleviated by greater standardisation. Third, there is a need for more robust methodologies for the estimation of the environmental performance, costs and range limitations of EVs to provide the industry, government and consumers with greater confidence.

Figure 9. Multiple influences on electric vehicle adoption



While these specific conclusions for the deployment of EVs may help to reduce some of the uncertainties we have identified, it is too early to close down the range of low carbon options for low carbon surface transport. While there has undoubtedly been significant technological, commercial and market progress for EVs in the last few years, it remains unclear whether this particular low carbon vehicle technology will be widely adopted. Other options such as hydrogen or more advanced and sustainable biofuels are still the subject of significant activity by government and industry, and could also achieve the breakthroughs required to reduce emissions.

3.4 Systemic uncertainties: natural resources and ecosystem services

This section discusses more systemic uncertainties that can have impacts across the whole energy system. Two areas of uncertainty are discussed in this section. First, it focuses on uncertainties associated with natural resource availability, including a focus on biomass and materials (more relevant to the low carbon pathway) and fossil fuels (more relevant to alternate pathway where low carbon ambitions are scaled back – but still a strong feature of the CCC low carbon pathway). Second, the section discusses potential impacts of energy system change on ecosystem services.

3.4.1 Natural resource impacts

There are significant differences in the availability of the natural resources used in the energy system. Some resources are finite (e.g. fossil fuels), some are renewable (e.g. biomass), and some are finite but potentially recyclable (e.g. critical metals). While availability estimates are often highly uncertain and contested, they can strongly influence the evolution of energy policies. This section focuses in particular on biomass and fossil fuels (using the example of shale gas) because these are particularly relevant to the fourth carbon budget pathway, and to contemporary energy policy debates. Critical metals are also of interest to these debates due to their anticipated use in a number of low-carbon technologies. At the time of writing a synthesis of UKERC's recent research review of critical metals resources is still under development[3].

[3] This will be published later in 2014. In the meantime, UKERC has created a 'handbook' that deals with the principal metals (http://www.ukerc.ac.uk/support/Materials+Availability+Handbook).

The section therefore draws on recent UKERC research that has reviewed of the range of estimates for biomass and shale gas resources (Slade *et al.*, 2011; McGlade *et al.*, 2013a; McGlade *et al.*, 2013b). It also reflects on some methodological complexities that are common to the assessment of these different resources (Speirs *et al.*, 2014).

A key source of uncertainty regarding fossil fuels is the lack of a universally agreed definition of the terms used to describe their availability. In some cases terms such as 'reserves' and 'economically producible volumes' are used interchangeably, while other studies subdivide the 'reserves' of a commodity depending on the uncertainty in its recoverability. Furthermore fossil fuels may also be classified according to the properties of the commodity produced, or the technologies used to produce it (e.g. 'conventional' or 'unconventional' oil) (Speirs *et al.*, 2014). There is no agreed definition of these terms, which can cause confusion resulting from: 1) equating inconsistent terms; 2) equating terms that contain differing assumptions; or 3) the use of identical sounding terminology when authors are in fact referring to different things.

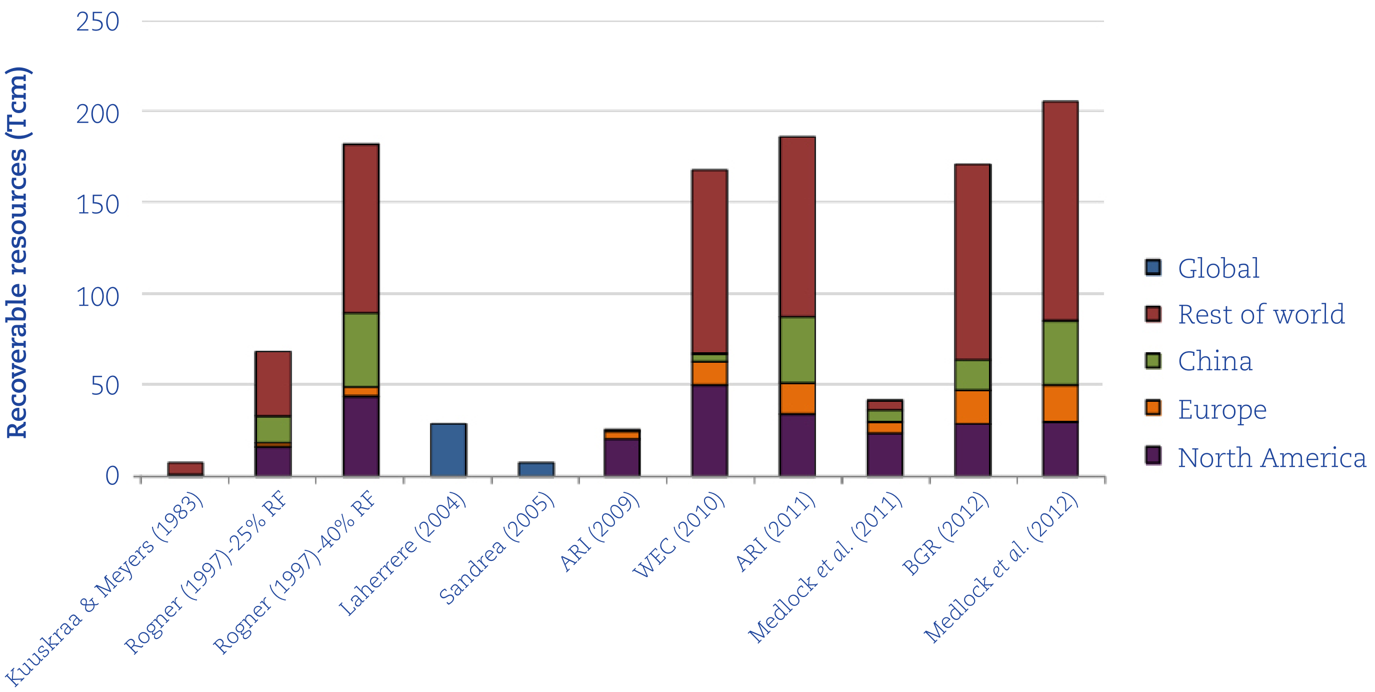
Uncertainties with respect to fossil fuel availability may be illustrated using shale gas as an example. Shale gas resources are mainly affected by three overarching types of uncertainty (McGlade *et al.*, 2013a; McGlade *et al.*, 2013b):

a. Definitional uncertainty, as described above
b. Data availability: the absence of any significant drilling experience for many regions of the world means that current resource estimates are not necessarily well founded. For some regions there may only be one estimate, while for some countries no contemporary estimates exist.
c. Methodological uncertainty: shale gas resources tend to be estimated either by a bottom up analysis of geological parameters or through the extrapolation of historical production experience. However both of these methodologies are sensitive to parameters that are poorly understood and contested in regards to shale gas, such as the recovery factor in the former approach and the production decline curve in the latter.

In addition to increased physical, technical and economic uncertainties, shale gas is subject to sustainability concerns (e.g. water availability) and socio-political uncertainties (e.g. impacts on landscape and property values). As recent UK controversies have shown, these concerns can render policy making problematic.

The result of these uncertainties is evident in the range of available shale gas estimates that were reviewed in 2012 by the European Commission's Joint Research Centre (Pearson *et al.*, 2012). A review of ten available estimates of global shale gas resources revealed a range from 7 trillion

Figure 10. Estimates of global recoverable resources of shale gas by sources considering regions outside North America. **Source:** Adapted from Pearson *et al.*, 2012.

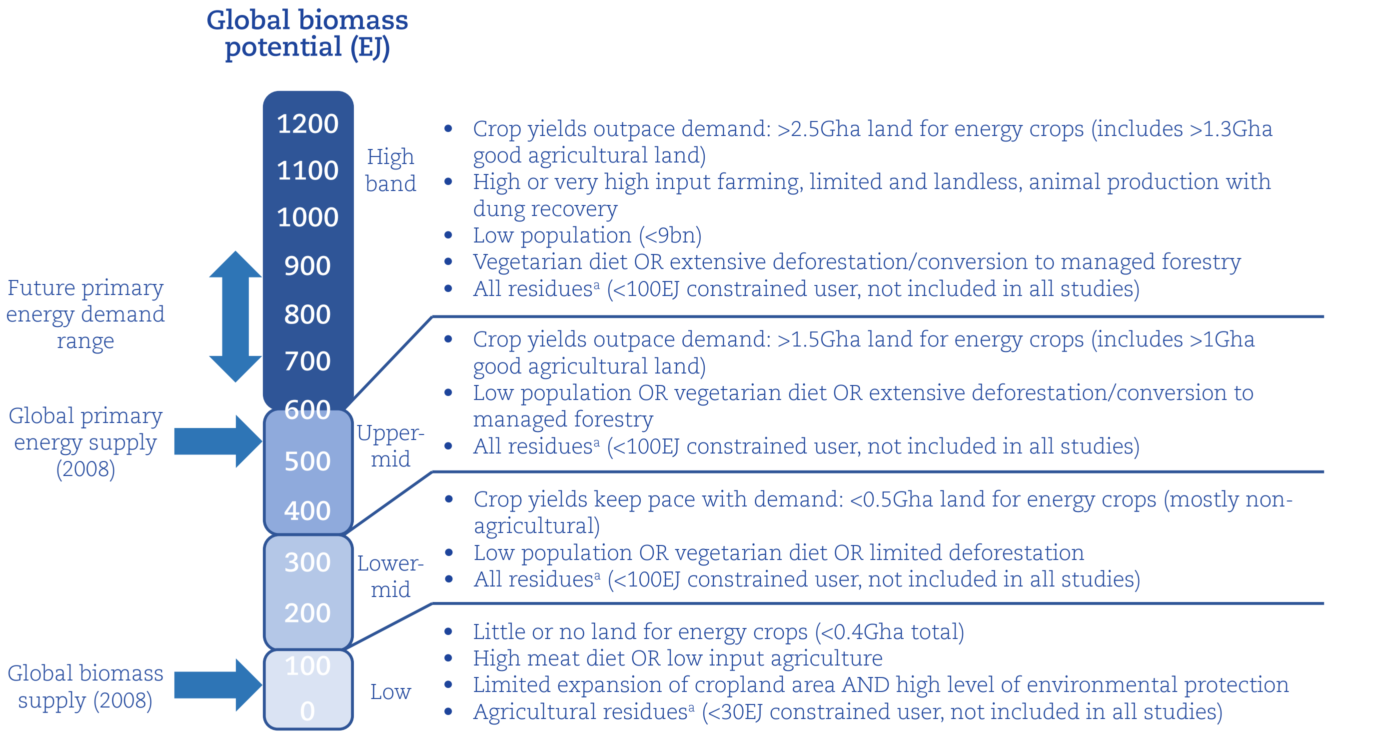


cubic meters (Tcm) to 206 Tcm, with a mean of 100 Tcm (Figure 10). These studies differ for a range of reasons including the inclusion of different geographical areas, differing assumptions regarding recovery factors, and differing definitions of recoverable resources.

Bioenergy is a renewable energy resource that has a significant potential to substitute for oil and other fossil fuels, but is subject to high uncertainty over its future availability. While the physical, technical and economic uncertainties are not well understood, biomass reserve and resource estimates are particularly sensitive to sustainability and socio-political uncertainties. The interlinkages between biomass and food production have resulted in a debate about whether large-scale adoption of bioenergy can be truly sustainable and the extent to which policy support can be justified (Slade *et al.*, 2011). In addition to food production and biodiversity concerns, conflicts can arise with established uses of natural resources, e.g. the pulp and paper and fibre board industries. If an increase in future biomass demand leads to higher prices, future biomass reserve estimates are likely to increase. This can be potentially problematic for policymakers, who will have to deal with wide ranges of biomass reserve and resource estimates in the short to medium term (Speirs *et al.*, 2014).

In order to try to improve the evidence base for policymaking and examine the reasons for the range of estimates, UKERC undertook a systematic review of the literature related to biomass availability (Slade *et al.*. 2011; Slade *et al.*, 2014). The review focused on the most influential estimates of biomass potential published since 1990. It found that the range of estimates is primarily driven by the choice of assumptions and that estimates should be viewed as 'what if' scenarios rather than forecasts or predictions (Slade *et al.*, 2014). The reason for this is that biomass resources cannot be measured directly and must be estimated, which may be done using several different types of models. While these can vary in complexity and sophistication, the review found that assumptions have a larger impact than methodological differences. The most controversial and influential assumptions relate to the future role of energy crops. The review examines these assumptions, focusing on yield predictions, water availability and sustainability assurance. In turn these depend on factors such as global population growth, dietary habits, the potential for crop yield increases, water availability, land allocation for nature conservation, soil degradation and the potential impacts of climate change on land productivity (IIASA, 2012; Lynd *et al.*, 2011). An overview of the impact of these factors on biomass availability is provided in Figure 11.

Figure 11. Essential preconditions for increasing levels of biomass production.
Source: Adapted from Slade *et al.*, 2011.



[a] Agricultural residues, forestry residues, wastes (dung, MSW, industrial)

In each band the minimum essential assumptions that must be included in global biomass models to achieve the given range of biomass potential are indicated. 'All residues' includes: wastes (dung, municipal and industrial), agricultural residues and forestry residues. Indicated global net primary productivity is aboveground terrestrial productivity only.

UKERC's review cautions that the literature provides limited information on what might be achieved in practice. This point is also highlighted by the Intergovernmental panel on climate change (IPCC) 2011 Special Report, which concludes that the technical potential of biomass depends on "factors that are inherently uncertain" and cannot be determined precisely while societal preferences are unclear.

3.4.2 Ecosystem service impacts

The analysis of potential ecosystem service impacts for this report (Dockerty *et al.*, 2014) focused on the entire life cycle, including upstream infrastructure, the fuel cycle (e.g. mining, processing), operation (e.g. power generation) and downstream activities (e.g. decommissioning). It included local (UK) and international impacts on a range of ecosystem services, split into four main categories (Haines-Young & Potschin, 2013):

- Supporting services (e.g. nutrient cycling, photosynthesis)
- Provisioning services (e.g. water, energy, food)
- Regulation services (e.g. pollution, climate control)
- Maintenance and cultural services (e.g. recreation)

The review of the evidence concentrated on supply side options including power generation technologies (nuclear power, carbon capture and storage, onshore wind and offshore wind) and natural resources (gas and biomass). The biomass assessment focused on domestically produced *Miscanthus* and short rotation coppice. These options were chosen since they feature strongly in the CCC's fourth Carbon budget analysis to 2030 – particularly in the CCC's four scenarios for reducing power sector emissions intensity to 50gCO_2/kWh by that date. The review included both systematic reviews of published studies focusing on local impacts within the UK and expert judgements regarding the global impacts of UK power generation.

The review shows that the evidence base is patchy and weak. Studies tend to be 'clustered' into relatively small areas of energy life cycles or related to relatively few ecosystem service indicators. This meant that expert judgements were often required to interpret and synthesise this data, especially with respect to global impacts. The relatively small number of studies identified may be due to limitations in the approach, reflect terms employed in database searches, or be indicative of a real lack of data. It is important to note that no sensitivity analysis was applied to the results. The individual impacts identified for different energy options from different studies can't necessarily be compared directly. Including differential weighting or valuation of impacts to try to make them more comparable would have been extremely challenging and time consuming, and may not have been feasible anyway given the currently immature state of knowledge regarding impacts on many ecosystem services. The global and local (UK) impacts of these options are summarised in Figures 12 and 13.

Overall, none of the impacts or uncertainties regarding ecosystem services identified by the review are likely to be sufficiently negative to rule out the combinations of energy supply options included within the CCC's fourth carbon budget pathway. More importantly, these options are likely to result in fewer negative impacts on ecosystem services and natural capital than the current reliance on fossil fuels. The available evidence suggests that a pathway that includes unconventional gas produced by fracking may have some negative impacts. It also shows that these impacts are much more uncertain than the potential impacts from conventional natural gas production.

The review found that the negative impacts on supporting, provisioning and regulating ecosystem services were mostly associated with the fuel cycle and operational stages of the energy options concerned. The main beneficial impacts relate to offshore wind and biomass through supporting ecosystem functions and atmospheric regulation. Biomass also has some positive impacts on soil and biodiversity when compared to conventional agricultural land uses. The largely conflicting or negative scores for cultural ecosystem indicators relate mostly to upstream and downstream stages of the energy systems – i.e. are associated with the built infrastructure. Information on downstream impacts for renewable energy sources was scant, perhaps because these technologies have only become widely deployed in recent years.

Figure 12. Global ecosystem service impacts of selected energy supply options

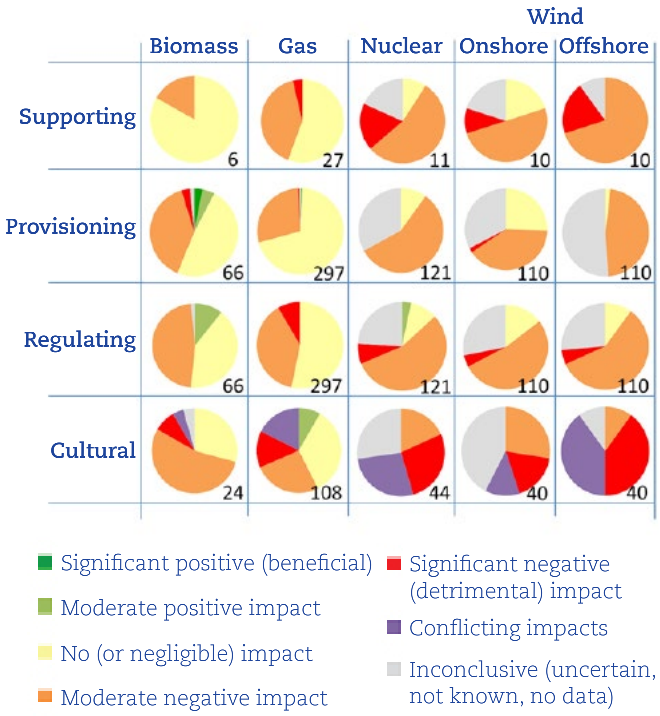
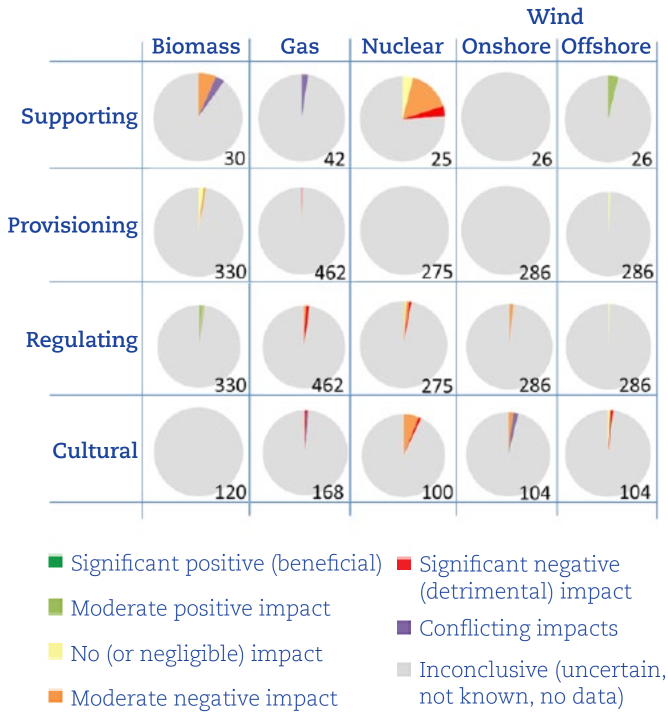


Figure 13. Local ecosystem service impacts of selected energy supply options



3.6 Systemic uncertainties: the role of public attitudes

One of the most important systemic uncertainties that will affect the achievement of the fourth carbon budget pathway is whether the political conditions will remain in place for electricity decarbonisation (and the wider energy sector emissions reductions) to take place. As this report has already noted, the increasing amount of controversy surrounding the direction of energy policy has increased the level of political uncertainty in the UK.

Understanding and engaging with public attitudes will be crucial in order to achieve a coalition for change between government, industry and publics (Butler *et al.*, 2014). In doing so, it will be important to go beyond simplistic discussions of 'public acceptance' of particular energy options – and to engage publics with the choices involved in low carbon policies and strategies. UKERC's recent in-depth research on public attitudes to energy system change led by the Cardiff University suggests that publics are concerned with a wider range of issues than expert debates suggest (Parkhill *et al.*, 2013). This research identified six groups of values that underpin public preferences. Note that these are not necessarily held by any one individual or by all publics, but they represent common 'cultural resources' upon which public preferences are formed.

They are:

- Efficiency and not wasting: being more efficient in the use of energy and minimising waste;
- Protection of environment and nature: being environmentally conscious and respectful of nature;
- Security and stability: making sure energy systems are safe, reliable. This applies to personal affordability and national availability of energy;
- Autonomy and power: being mindful of the autonomy and freedom at national and personal levels;
- Social justice & fairness: developing energy systems that are open, transparent and fair, and take into account people's ability to lead healthy lives; and
- Improvement and quality: a long-term trajectory for energy systems that improve quality of life.

As these values suggest, UKERC research has found that publics are interested in how energy transitions should be organised and paid for, not just in what technologies might be deployed. While energy policy framings such as those in the CCC's fourth carbon budget report reflect some of these values, they do not engage with the full range of public concerns (Butler *et al.*, 2014). This is particularly apparent in three areas. First, values of social justice and fairness and autonomy and power focus specifically on the equity implications of energy systems (particularly fuel poverty) and the wider market arrangements that govern the energy system. While the CCC has considered the impacts of the fourth carbon budget pathway on fuel poverty, the number of fuel poor households has continued to rise in recent years (Fuel Poverty Advisory Group, 2013). Furthermore, wider policy discourses have been reluctant to question the structure of the energy market. Although the recent announcement of a review by the Competition and Markets Authority is a step in this direction, it is unlikely to ask some of the fundamental questions within public framings.

Second, policy framings relating to values of protection of the environment and nature – including those in the CCC fourth carbon budget – focus primarily on carbon emissions. While this is in line with public concerns, it does not tend to include wider concerns about the impact of current and future energy systems on the natural environment, such as other forms of pollution associated with fossil fuels and their extraction. As discussed earlier in this report (section 3.4), the impacts of low carbon technologies and renewable resources on ecosystem services are very uncertain due to a lack of good empirical evidence.

Third, although the CCC and the government place a significant emphasis on energy security, this does not necessarily align with public values of security and stability. Policy discourses tend to focus on national energy security, while publics see security from a more local and personal perspective. This local framing is often linked to their ability to access and afford energy (and the services it provides). As recent controversies confirm, publics do not regard energy as affordable at present. UKERC research also shows that relative affordability and price stability (as opposed to universally low prices) is important.

Turning to the specific technical options set out by the CCC to meet the fourth carbon budget, many of these align with public values – including measures to reduce energy demand, to increase the use of renewable energy, and to move away from fossil fuels. Support for nuclear power is more conditional, and is likely to only extend to replacement rather than expansion.

There are, however, some options that are viewed by publics as 'non transitions' in the CCC and government plans (Butler *et al.*, 2013) options that were found to be seen as problematic because they do not fit with values associated with environmental protection and long-term improvement and quality. These include carbon capture and storage (since it enables the continuing use of fossil fuels) and bioenergy (because of concerns about their sustainability). To summarise, the technocratic emphasis of the CCC analysis (and indeed of much government policy analysis) misses out some issues that are central to public framings, and therefore fail to properly account for additional layers of political uncertainty associated with such public views. This includes the way in which energy system change should be organised and paid for, how equity concerns should be addressed, and what the balance of responsibility for change should be between the public and private sectors and civil society.

4

Staying on Course?

Having set out some of the key uncertainties for the implementation of the UK's low carbon transition, it is important to ask what could be done to reduce or manage them. Table 3 summarises the uncertainties that have been identified in the report, their complexity and potential impact, and further actions that could be taken to mitigate them. In the Table, a distinction has been made between more bounded 'instrumental' uncertainties that related to specific technologies or parts of the energy system and broader 'systemic' uncertainties that could have an impact on the overall direction of energy system development.

The assessments summarised in the table are designed to provide rough 'high level' guide to the extent and importance of the uncertainties concerned. The second column of the table draws on methodological research for this project (Davies *et al.*, 2014). This identifies different levels of complexity for decision-making in uncertain contexts. If complexity is low, the number of variables – and the range of uncertainty with respect to those variables – is bounded and well known. By contrast, high levels of complexity implies that there are multiple variables, some of which are difficult to characterise because the full range of potential outcomes are not well known. The third column suggests how large an impact each uncertainty could have on the achievement of the fourth carbon budget pathway if action is not taken to mitigate it.

The fourth column of the table summarises some actions that could be taken to partly or fully resolve the uncertainty, or to inform better decision making if significant uncertainty is likely to remain over the period to 2030. These actions are discussed further in the conclusions to this report (see section 5). Finally, the fifth column suggests which actors could take primary responsibility for acting to mitigate or better understand the uncertainty concerned. Within this column, the generic term 'citizens' has been used to denote the involvement of individuals or communities, either as consumers or in broader roles. Similarly, the term 'businesses' has been used to include a range of different types of business – from large-scale utilities to small firms involved in the energy efficiency supply chain. Roles for government are also suggested at a number of levels – including national, devolved and local government within the UK, and foreign governments in cases where international policy processes are likely to be important.

The analysis summarised in the Table highlights three main sets of issues. First, there are significantly higher levels of 'instrumental uncertainty' about pathways to reduce emissions from the heat and transport sectors than there are about the decarbonisation of the electricity sector. This has advantages as well as disadvantages. For heat and transport, there is still time for options to be kept open and for testing, demonstration and evaluation of different technologies and infrastructures. For electricity, a limited set of low carbon technologies could play a significant role in a low carbon electricity system in 2030. In the longer term, other technologies may become important. But in the period to 2030, the main instrumental uncertainties relate to the demonstration, financing and deployment of that limited set of technologies. Of course, the wider systemic uncertainties highlighted in this report will also have a significant impact on the mix of technologies within a low carbon electricity system – and on which low carbon heat and transport options eventually turn out to be the most promising routes to emissions reduction.

Second, the uncertainties that have been discussed in this report are interdependent. If particular uncertainties are not managed or resolved effectively, that can have a knock on effect - and can exacerbate other uncertainties. For example, policy (and political) uncertainties about incentives for the deployment of low carbon electricity generation will tend to increase technological and financial uncertainties. As discussed in section 3 of this report, the flow of finance to the UK power sector, and the technological development and learning that this would enable, will be significantly curtailed if policy frameworks do not make investment attractive enough.

Another example is the interaction between electricity, transport and heat. If progress with electricity decarbonisation does not proceed as envisaged in the fourth carbon budget pathway, this will reduce the options available for heat and transport decarbonisation. Our analysis has shown that there are other, sometimes complementary, options for heat and transport decarbonisation. However, this would make uncertainties about these other options such as energy efficiency, district heating, hydrogen vehicles and the availability of bioenergy more important.

Third, it is also important to consider the implications of the wider political uncertainties discussed in section 1 of this report. There are clear interactions between the uncertainties discussed in this report and these political uncertainties. Within the political debate, some have argued that the UK should downgrade its commitment to reducing emissions because this is perceived to be too costly. But placing less emphasis on emissions reduction is not a cost or risk free option. Other uncertainties, and their potential impacts, will be much more important in future if emissions do not fall as suggested by the 4th carbon budget analysis.

Clearly, if the UK does not reduce emissions, and this trend is matched by similar trends elsewhere in the world, the likelihood of significant climate change will increase (IPCC, 2014). This would make it much more likely that the UK and other countries would be subject to large impacts from climate change, and all of the costs and other implications associated with those impacts. Perhaps more immediately, a failure to shift quickly enough to a low carbon energy system will do little to mitigate uncertainties about the price and availability of fossil fuels. Like many industrialised countries, the UK's energy system is largely dependent on fossil fuels. If fossil fuel prices remain high, or rise further, consumer bills are likely to be higher in 2020 than they would be if low carbon policies were pursued successfully (DECC, 2013b).

While it is impossible to predict future fossil fuel prices, it would not be prudent to assume that there will be a low fossil fuel price future. The shale gas revolution in the United States has led to low natural gas prices in that country, but there are significant doubts about the extent to which shale resources will be developed in the UK – and whether such developments would have a similar effect on prices (Stevens, 2013). This reinforces the need to pursue many of the strategies set out in Table 3, particularly those such as energy efficiency and diversification that are designed to mitigate the exposure of consumers to the energy security risks of fossil fuel dependency.

Table 3. Key uncertainties for meeting the 4th Carbon Budget

	Complexity	Potential impact on fourth carbon budget	Potential actions to reduce/ manage uncertainty	Primary responsibility
Instrumental uncertainties				
Availability of finance for low carbon power generation	Medium	High	• Implementation of electricity market reform • Financial risk reduction measures • Consider alternative 'vehicles' for investment	• Central government • Financial community; Green Investment Bank • Developers, utilities and equipment companies
Commercialisation of low carbon power generation technologies	Medium	High	• Long term policy support • Demonstration funding for CCS • Evaluations/learning to inform policy adjustments	• Central government; other LCICG members • Developers, utilities and equipment companies • Research community
Diversity of heat decarbonisation pathways	High	Medium	• Demonstrations of technologies and infrastructures • Evaluations & learning	• Central, devolved and local govt • Other LCICG members • Businesses (utilities and equipment suppliers) • Citizens (households and communities)
Heat pump performance	Low	Medium	• Incentives for demonstration/deployment • Learning and engagement with consumers (including businesses)	• Central, devolved & local govt • Other LCICG members • Citizens (households) and businesses • Research community
District heating investment/ business models	Medium	Low	• Demonstrations (including business models) • Capacity building • Extension of economic regulation to heat networks	• Central, devolved and local govt; Ofgem • Businesses (esp. utilities, supply chain) • Citizens (households and communities)
Energy efficiency improvements/ demand reduction	Medium	High	• Stronger policy incentives, especially for homes and small/medium sized businesses	• Central, devolved and local govt • Businesses (esp. supply chain) • Citizens (households and communities)
Diversity of transport decarbonisation pathways	High	Medium	• Support for diversity of experiments and demonstrations • Learning & evaluation of experiments and demos	• Central, devolved and local govt • Businesses (esp. oil, utility and vehicle companies) • Citizens (households and communities) • Research community
Electric vehicle adoption	Medium	Medium	• Financial certainty about taxation regime • Standardisation of charging and payment systems • More robust/ independent performance metrics	• Central government • Businesses (esp. manufacturers, DNOs) • Citizens (early adopters) • Research community

Table 3 cont. Key systemic uncertainties for meeting the 4th Carbon Budget

Systemic uncertainties	Complexity	Potential impact on fourth carbon budget	Potential actions to reduce / manage uncertainty	Primary responsibility
Fossil fuel availability and price	High	High	• Energy efficiency • Diversity of supplies, routes and storage • Carbon pricing	• Central government and Ofgem • EU / other governments • Businesses (esp. oil and gas companies) • Citizens (including communities)
Bio-energy availability and price	High	Medium	• Resource efficiency • Sustainability standards • Diversity	• Central government • EU / other governments • Businesses and citizens
Scarce materials	High	Low	• Recycling • Resource efficiency • Diversity	• Central government • Businesses (esp. technology providers)
Ecosystem service impacts	High	Low	• More research to strengthen evidence base • Decision-making tools	• Central government • Research community • Businesses
Public attitudes to energy system change	High	High	• Genuine political engagement with respect to energy systems change	• Government • Citizens
Political commitment to a low carbon transition	Medium	High	• Reinforce long-term policy framework with detailed strategies, plans and policies • Confirm the fourth carbon budget	• Government and Parliament • Citizens • Businesses

5

Conclusions

This report has discussed some of the key uncertainties facing the UK's planned low carbon transition, and also identified policies and strategies to mitigate or better understand these uncertainties. At the outset, the report acknowledged the growing political uncertainties about the future direction of UK energy policy. While the government remains committed to emissions reduction, and has legislated carbon budgets to the late 2020s, political controversy about energy policy goals has the potential to compound some of the challenges this report has discussed in detail.

As the report has shown, this is just one example of the interdependent nature of the uncertainties faced by the government, industry, citizens and communities. It has also shown that these uncertainties operate on different levels – and have widely different potential impacts. There are specific 'instrumental' uncertainties such as those that will affect the adoption of electric vehicles or the flow of investment to the UK power sector. There are also wider 'systemic' uncertainties that could have more pervasive implications such as the impacts of energy system development on national and global ecosystems, and the role of public attitudes and values in shaping change. Some of these uncertainties can be mitigated to some extent by government and other actors. Others cannot, and imply a need to keep options open or to develop and apply new methods of analysis to understand them more fully.

In common with the CCC's analysis, this report emphasises the importance of power sector decarbonisation by 2030. Our analysis of investment capital requirements shows that there is no shortage of capital per se. However, further changes to policy frameworks, market structures and business models may be needed to attract that capital to the UK power sector. This is partly due to the significant risks associated with capital-intensive low carbon power generation technologies, some of which are still in their demonstration and early deployment phases. It is also because it is likely that a diversity of investors will be required, given the limits on the potential availability of investment capital from traditional utilities. The recently announced Competition and Markets authority review of the energy market should consider this diversity as part of its deliberations.

One of the significant challenges for the power sector to 2030 is that there are limited large-scale low carbon options to 2030. All of them face different economic, technical and political challenges. Of course, smaller scale technologies such as solar PV and decentralised bioenergy plants have a potentially significant role to play too. Given the financial resources required and the political tensions about some of these technologies (e.g. wind power), it will be tough for the government to keep open all options in DECC's 'low carbon race'. Limits to political capital may be just as important as any constraints on the flow of financial capital. Once there is more information about costs and cost trajectories, decisions may need to be made to focus on those technologies that are the most cost effective.

By contrast, there is more flexibility with respect to heat and transport decarbonisation – particularly over the period to 2030. While there has been a focus on electrification of these sectors in the analysis conducted by the CCC, government and other bodies, delays with electricity decarbonisation would not necessarily be a show stopper. However, it would mean that other means of decarbonising heating and transport would need to receive more attention – and that the impact of uncertainties about these would be potentially greater. Furthermore, our analysis shows that the use of electric heating technologies is still likely to be important under this scenario in the longer-term.

Since it is not yet clear what combination of electrification and/or other low carbon options will be the best route for reducing transport and heat emissions, there should be a continuing emphasis on experimentation and demonstration. It is also important that the lessons from experiments are learned and shared, especially because a range of different funding bodies, businesses and other organisations are often involved. Many demonstrations are already underway or planned. In some cases, these are needed to test and refine relatively new technologies. But in many cases, the purpose of such demonstrations is to learn about non-technical factors such as consumer attitudes, business models and the extent to which regulatory frameworks need to change. For example, district heating networks are not new but their relative unfamiliarity in the UK mean that there are significant non-technical barriers to investment.

One corollary of this greater flexibility is the need to place more emphasis on energy efficiency, particularly in relation to the use of heat in buildings. Further progress with energy efficiency can help to buy time if electricity decarbonisation and/or the deployment of heat pumps and associated electricity network upgrades are not as successful as planned. Furthermore, energy efficiency will also help to reduce consumers' bills and to make them more resilient to energy security risks – particularly those that increase fossil fuel prices. It is ironic that the government's level of ambition with respect to household energy efficiency policy has been cut back at a time when consumer bills are particularly high.

The systemic uncertainties discussed in this report also merit more attention by policy makers and other actors. In particular, there is a need to move beyond narrow framings of public attitudes. All too often, expert debates on energy policies and choices are potentially counter-productive. Some of these debates still focus on 'persuading the public to accept' a given set of technologies rather than engaging the public in the kind of energy system they would like to see. In addition, public views are sometimes represented in media and political discourse about energy systems as fickle, dogmatic, and irrational (e.g. Wintour, 2014).

UKERC's research shows very clearly that broader engagement with public perspectives is both desirable and necessary. This could not only increase the chances of public support for change, it could also open up possibilities for compromise within public responses. This could include, for example, more acceptance of less desirable aspects of system change (e.g. some continued fossil fuel use) in a context where there is a greater sense that the full range of responses and concerns are being considered, and where there is a clear long-term vision for change around which diverse publics can coalesce. This research also shows that visions for change should go beyond technologies, and should also focus on the way in which the energy system could be organised and paid for.

The transition to a low carbon energy system implies a significant reduction in the use of fossil fuels. Scaling back the UK's low carbon ambitions would risk prolonging our reliance on fossil fuels, and the exposure of consumers and the UK economy to the potential impacts of high fossil fuel prices. However, natural resources will continue to be important if the low carbon transition continues as planned. This report has shown that the availability and price of fossil fuels and bioenergy resources is subject to very large uncertainties. Furthermore, controversies and concerns about these resources – particularly shale gas and biomass – may limit the extent to which they can be developed and used. In both cases, their use in the UK will be partly affected by global trends.

Similarly, the transition to a low carbon energy system will have uncertain implications for ecosystems – and the services those ecosystems provide. All four of the low carbon power generation scenarios analysed by the CCC to 2030 will have upstream consequences for ecosystem services outside of the UK and downstream ones within it. While the evidence review suggests that low carbon technologies will have fewer and/or less serious impacts than fossil fuels, it also shows that the evidence base is weak. Significant further research is needed to strengthen this evidence base. Furthermore, new techniques and databases are required to inform decisions about energy system change within the UK, and to link these with their global ecosystem consequences.

Finally, this report has shown that it is not possible to resolve many of the uncertainties that will impact on the UK's low carbon plans – at least not in the short term. This is what makes policy making particularly challenging. But this does not mean that nothing can be done. The report has highlighted a range of strategies that could be used in the face of these uncertainties. In some cases, it makes sense to support a diverse range of potential technologies and strategies – and to experiment and learn about what options are the most effective. As our methodological research has discussed (Davies *et al.*, 2014), there are also a range of tools and techniques that can be applied to understand or manage such uncertainties more effectively. Of particular importance are methods that can deal with more systemic uncertainties, and can help to develop responses that are robust to a range of potential outcomes.

6

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